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Report 1635

DEPARTMENT OF THE NAVY
DAVID TAYLOR MODEL BASIN

HYDROMECHANICS

AERODYNAMICS

STRUCTURAL MECHANICS

APPLIED MATHEMATICS

CRITERIA FOR HUMAN REACTION TO ENVIRONMENTAL VIBRATION ON NAVAL SHIPS

by

E. Buchmann, Ph.D.

STRUCTURAL MECHANICS LABORATORY
RESEARCH AND DEVELOPMENT REPORT

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E. Buchmann, Ph.D.
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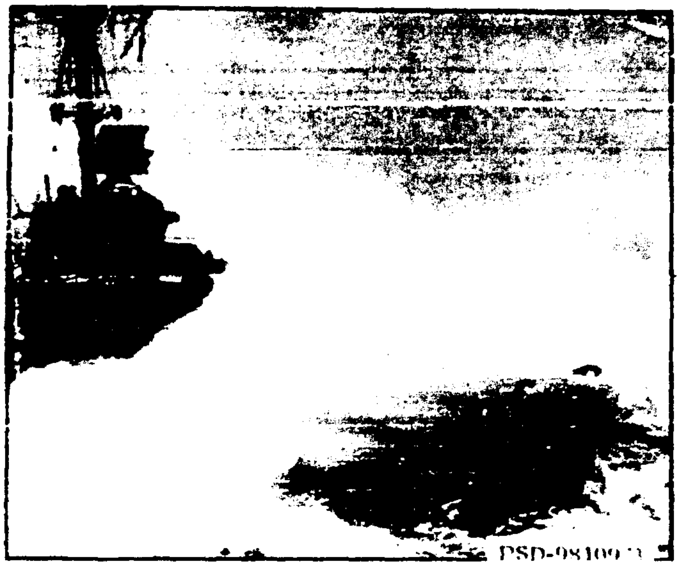

Destroyer in a Heavy Sea

What are the human reactions to the environment?

ABSTRACT

A search of existing literature on human reactions to vibrations was made to obtain a guide for establishing norms for crews on naval ships. Such norms are recommended herein as a result of this study. Further research programs are outlined.

INTRODUCTION

The David Taylor Model Basin was directed by the Bureau of Ships to provide criteria for the maximum permissible hull vibration for naval ships.[1] In establishing vibration standards, the following possibilities must be considered:

(a) Vibrations may seriously impair the proper functioning of mechanical and electrical equipment.

(b) Vibrational accelerations may cause structural damage.

(c) Vibrations may be a source of annoyance and discomfort to members of the crew and may interfere with the efficient performance of their duties.

It is known that vibration of a certain nature and in a particular location will be a source of discomfort to the crew of a ship and may, at times, cause certain limitations to their work although it causes no structural or equipment failure. Thus, it would be advantageous to establish tolerance limits within which designated percentages of personnel would fall. In addition, such a criterion for human response to vibrations could be coupled with an appropriate criterion for structural and machinery vibration to yield overall acceptable vibration levels for naval vessels.

This report defines levels of motions and vibrations to which crew members are exposed during surface ship operations. Criteria for human reactions to vibrations are recommended on the basis of an evaluation of the existing literature in this area. The levels of vibration are also compared with those for structural items and machinery. No attempt is made to evaluate all work in this field; only that considered pertinent to problems arising from shipboard vibration is included.

SUGGESTED CRITERIA FOR ENVIRONMENTAL VIBRATIONS OF SHIPS

The Model Basin has accumulated a large amount of data on wave-induced rigid-body motions of ships under many operating conditions and in many sea states. It has also conducted a study of the frequency of occurrence of the various magnitudes of ocean waves.[2] From these studies, it was found that wave height, wave length, and wave-induced ship motions may be expressed statistically in the form of a single parameter Rayleigh distribution when environmental conditions are steady and, in the form of a two-parameter logarithmic normal distribution when a long period of time is considered.

Shipboard vibrations are usually measured in quiet sea conditions. These vibrations may be due to propeller excitation, unbalance of propeller-shaft system, machinery, or transient vibration during maneuvers. Vibrations in quiet waters must be increased to allow for rough-water operations, slamming, and maneouvering.[3,4] With this information, it is possible, in principle, to predict for a particular type of ship and specific sea conditions, the probability of occurrence of wave-induced motions and the amplitude of the vibrations that will result.

The motions and vibrations of a ship depend largely on the sea state encountered. Ships of various classes, however, react differently to the usually established definition of a sea state, depending mainly on the ratio of wave length and height to the length of a ship. A short ship, for example, may vibrate violently in a sea state in which a long ship may not be very much affected.

In this report, all ship motions and vibrations will be divided into classes and related to the human reaction to vibration. It will be shown how these classes of vibration correspond to the classes suggested for human reactions. For convenience, the classes of ship vibrations will be identified by the term "vibration level" and numbered from I through IV. Each vibration level for a given ship is associated with its length and a sea state of defined wave length and height. Knowledge of the probability of occurrence of such a sea state allows an estimate of how frequently a ship will encounter sea states up to this level. The motions of a ship corresponding to this sea state can also be estimated.

Vibration levels are defined arbitrarily in Table 1.

TABLE 1

Definition of Vibration Level and Corresponding Sea State

Vibration Level	Corresponding Sea State	Vibration Level	Corresponding Sea State
I	$L_W \le \frac{1}{3} L_S$*	III	$L_W \le \frac{1}{1.5} L_S$
	$H_W \le \frac{1}{120} L_S$		$H_W \le \frac{1}{30} L_S$
II	$L_W \le \frac{1}{2} L_S$	IV	$L_W \le L_S$
	$H_W \le \frac{1}{80} L_S$		$H_W \le 34$ ft

*Here L_S is ship length in feet; H_W is wave height in feet; and L_W is wave length.

These arbitrary definitions are justified only because no other levels have yet been defined.

The probability of the occurrence of a sea state may be obtained for certain ocean areas from evaluation of weather station observations. Observations for the Weather Station C, 52°N 37°W, North Atlantic, for instance, have been made over many years.[5] The percentage of time for sea conditions less severe than those for a given vibration level is plotted against ship length in Figure 1. As expected, the curves show that long ships are relatively less affected by severe sea conditions than are short ships.

The heave, roll, and pitch motions of a ship corresponding to a given probability are known for certain classes of ships and are being developed for other classes. These motions follow a Rayleigh distribution during short periods of, say, 4 hr during which the sea state does not change.

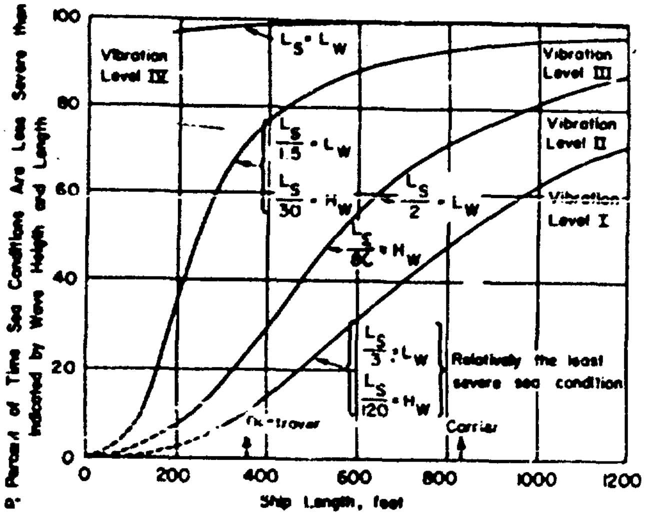

Figure 1 – Percent of Time for Sea Condition Less Severe than Indicated Vibration Level Versus Ship Length

This distribution is defined by one parameter, the mean square value of all the motions during this period. Over a long period the root mean square of all short period motions for a given sea state follows a logarithmic normal distribution for all possible sea states. Figures 2 through 4 show the probability of not exceeding root-mean-square values for heave, roll, and pitch for ESSEX-Class carriers and DD692-Class destroyers. The curves in Figures 2 through 4 were derived from data published in References 6 and 7. The probability of occurrence up to a certain vibration level for a given ship length is taken from Figure 1 and listed in Table 2 for destroyers and carriers. Extreme values may occur in such a distribution; however, it is believed that a rare extreme value does not significantly affect the human reaction. Therefore, only motions within 2.27 times the root-mean-square values are considered.

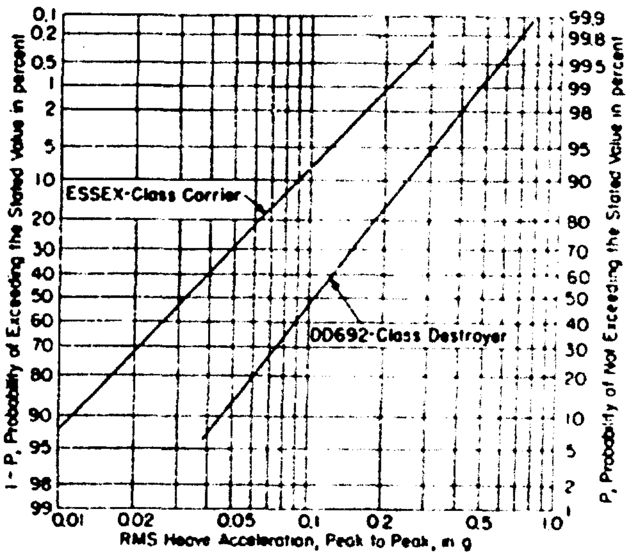

Figure 2 – Probability of RMS Heave Acceleration Not to Exceed Stated Values

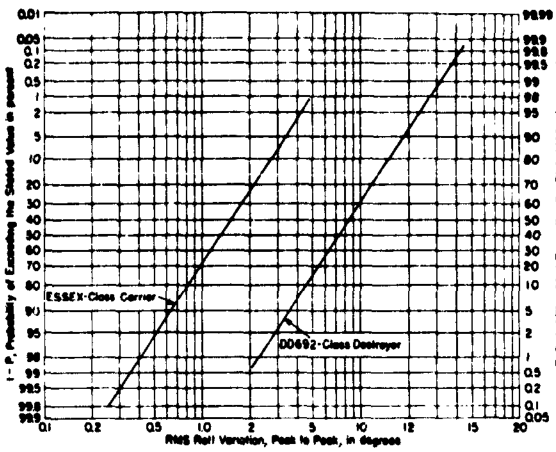

Figure 3 – Probability of RMS Roll Angle Not to Exceed Stated Values

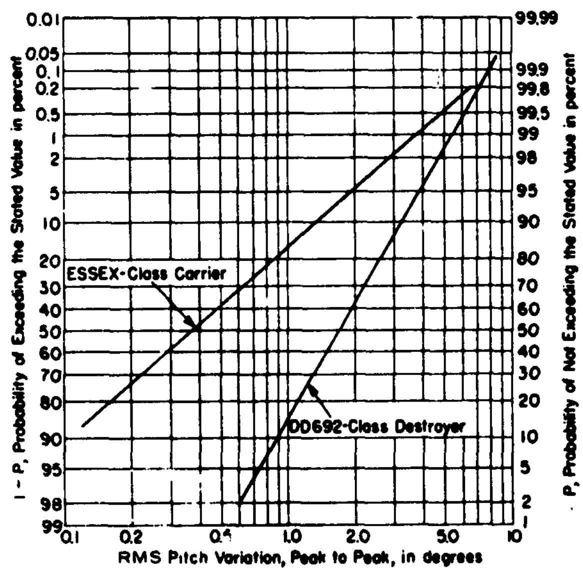

Figure 4 – Probability of RMS Pitch Angle Not to Exceed Stated Values

TABLE 2

Probability of Occurrence up to the Defined Vibration Levels for Carrier and Destroyer

Length, L_s ft	Carrier 820	Destroyer 380
"Vibration Level"	Percent of Time up to Vibration Level (from Figure 4)	
I	50	11
II	75	25
III	94	73
IV	99.5	99

There are, in general, areas of various intensities of motion throughout the ship. The main deck near the fantail is particularly interesting because this area usually experiences large vibratory levels. The values for roll, heave, and pitch corresponding to the "vibration level" probability are taken from Figures 2 through 4 and listed in Table 3. They are used for calculating the vertical accelerations that may be expected at the fantail. These acceleration values are listed for carriers in Table 4 and for destroyers in Table 5. Also included are the vertical accelerations for whipping and vibratory motions up to about 15 cps. The latter data were obtained from measurements in smooth seas.[8,9] Measured amplitudes of accelerations have been increased to allow for rough sea conditions.[3]

TABLE 3

Heave, Roll, and Pitch on Carriers and Destroyers for Four Vibration Levels

Vibration Level	Heave g+	Roll deg+	Pitch deg+
Carrier			
I	0.03	1.2	0.32
II	0.05	1.8	0.70
III	0.10	2.9	1.60
IV	0.23	5.0	4.50
Destroyer			
I	0.04	3.2	0.8
II	0.06	4.5	1.1
III	0.14	9.0	2.0
IV	0.42	25.0	5.0

+Values are taken from Figures 2 through 4, multiplied by 2.27, and divided by two to obtain single amplitudes.

TABLE 4

Environmental Vertical Rigid Body and Vibration Accelerations near Fantail of Carriers for Four Vibration Levels

Mode of Motion	Frequency cps	Single Amplitude of Acceleration, g I	II	III	IV
Roll	0.068	0.005	0.007	0.012	0.020
Pitch	0.082	0.015	0.034	0.080	0.200
Heave	0.100	0.030	0.050	0.100	0.230
Whipping	0.790	0.006	0.010	0.020	0.580*
	1.400	0.006	0.010	0.020	0.810*
Vibration	5.0	0.040	0.050	0.060	0.080
	6.0	0.020	0.020	0.030	0.040
	7.0	0.050	0.060	0.080	0.100
	8.0	0.060	0.080	0.100	0.120
	9.0	0.060	0.080	0.100	0.120
	10.0	0.100	0.130	0.170	0.220
	10.6	0.180	0.240	0.300	0.360
	15.0	0.200	0.270	0.340	0.400

*Slamming

TABLE 5

Environmental Vertical Rigid Body and Vibration Accelerations near Fantail of Destroyers for Four Vibration Levels

Mode of Motion	Frequency cps	Single Amplitude of Acceleration, g			
		I	II	III	IV
Roll	0.120	0.030	0.040	0.100	0.200
Pitch	0.140	0.060	0.090	0.150	0.400
Heave	0.200	0.040	0.060	0.140	0.420
Whipping	1.320	0.005	0.010	0.020	1.700*
	2.750	0.008	0.010	0.020	3.000*
Vibration	4.5	0.010	0.013	0.017	0.020
	6.5	0.020	0.025	0.030	0.040
	8.3	0.090	0.120	0.150	0.180
	10.0	0.030	0.040	0.050	0.060
	12.5	0.400	0.500	0.600	0.800
	14.5	0.400	0.500	0.600	0.800

*Slamming

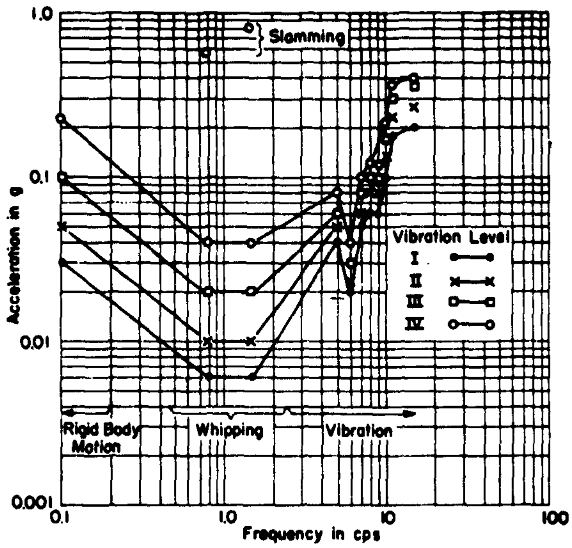

Figure 5 – Accelerations for Four "Vibration Levels" Plotted Against Frequency for ESSEX-Class Carriers

The results of Tables 4 and 5 are seen more easily in Figures 5 and 6 where the accelerations are plotted against frequency. The vibration levels have been divided into three frequency ranges:

(a) Frequency range for the rigid-body motion. Heave, pitch, and roll cause acceleration ranging from about 0.03 g for Vibration Level I (smooth sea state) to about 0.4 g for Vibration Level IV (rough sea state). The conditions set up for the relation of ship length to sea state is such that the accelerations for the various vibration levels are almost the same for the two classes of ships. The frequencies increase for the shorter ship.

(b) Frequency range for flexural vibrations (whipping). The whipping accelerations are usually smaller than the rigid-body accelerations. The accelerations for the various vibration levels are such that they are almost the same for both classes of ships. Again, the frequencies increase for the shorter ship.

(c) Frequency range for machinery and propeller-excited vibrations. The accelerations increase rather rapidly with increasing frequencies from about 4 to 10 cps and are almost constant for higher frequencies. The accelerations for destroyers are almost twice as large as those for carriers. For each ship class in turn, the acceleration increases almost by a factor of two when the ship operates in a rough rather than in a smooth sea.

A person at the fantail of the ship is subjected to all these accelerations at various frequencies at the same time. It is, therefore, of interest to see how classes of human

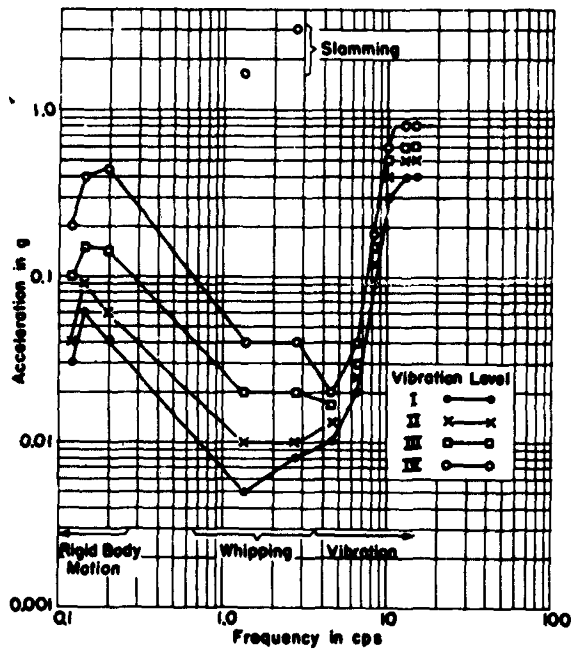

Figure 6 – Accelerations for Four "Vibration Levels" Plotted Against Frequency for DD 692-Class Destroyers

reactions to vibrations compare with the vibration levels as experienced at the fantail of a ship. Findings of human reactions to vibration are, therefore, discussed in the next section.

EXPERIMENTAL FINDINGS FROM EXISTING LITERATURE

The problem of human reaction to vibrations is probably as old as the problem of transportation itself.

While efforts have long been made to diminish vibration effects, systematic testing of human reactions to vibrations started only during the last 50 years. The nature of the tests and the classification of results suggest that only a statistical evaluation will tend to minimize errors in the judgment of test populations. A very large number of tests and subjects would be required to allow for the many possible parameters involved. Some of these parameters are:

(a) Direction of vibratory motion with respect to the body.

(b) Waveform of the vibrations.

(c) Uni- or multi-directional vibrations.

(d) Characteristics of test subjects.

(e) Condition of subjects during the tests.

(f) Environmental conditions such as temperature, humidity, ventilation, odors, noise, and so forth.

(g) Activity of the individuals observed.

Not all these parameters have been investigated.

Among the most extensive studies were those by Jacklin and Liddell[10,11] and Reiher and Meister.[12,13] The general procedure was to describe levels of comfort and discomfort prior to the test. Then the subjects stood or sat on vibrating platforms and were exposed to sinusoidal vibrations in three orthogonal directions. The frequency and amplitude of vibrations at various comfort and discomfort ranges were recorded according to the sensations experienced by the subjects.

Figure 7 summarizes the Reiher and Meister study on human reactions to vibrations up to 70 cps. All results are expressed in accelerations for given ranges of frequency and classified according to the corresponding reaction of the test population. The subjective nature of such test results is indicated by the gradual shading from one class of human reaction to another, ranging from "very weak" to "unbearable."

Figure 7 shows that the classes of human reactions can be approximated by curves, allowing a representation in the form

$$K = cdf^n \qquad [1]$$

where K is a value to correspond to the various classes of human reaction called reaction factor,

d is single amplitude of displacement in inches,

f is frequency in cycles per second,

n is an exponent derived from Figure 7, and

c is a constant as listed in Table 7

Thus, it can be derived from the slope of the lines in Figure 7 that as the frequency of vibration increases, human reaction is proportional to the jerk (i.e. to the derivative of the acceleration with respect to time), acceleration, velocity, and displacement of the vibratory motion, in that order. The value of K is connected with a class of human reaction and indicates a sensitivity of the body, as shown in Tables 6 and 7.

The factor c changes with frequency range in a rather complicated way. The last column in Table 6 indicates the effect of vibration on "work." There was no indication as to what kind of work was considered or how the measurements were made.

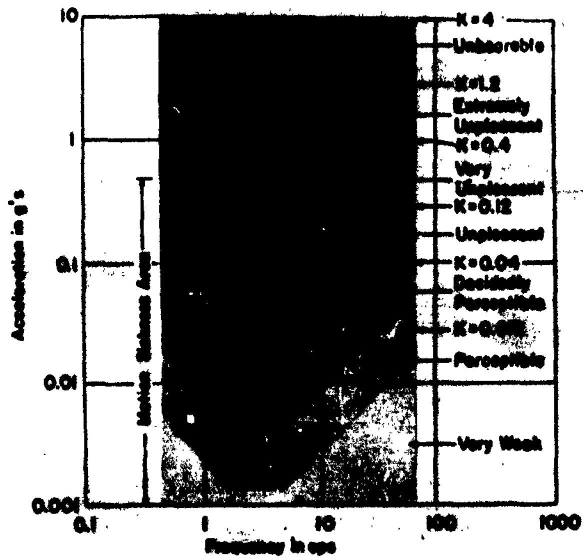

Figure 7 – Human Reaction to Vibrations up to 70 cps

These plots were developed from References 12 and 13.

TABLE 6

Values of Reaction Factor K for Various Classes of Human Reaction to Vibration

Based on References 12 and 13 and published in Reference 14.

Reaction Factor K	Class of Human Reaction to Vibration	Effect on Work
Up to 0.012	Very weak	Unhindered
0.012 – 0.040	Perceptible; unpleasant if exposed for hours	Slightly hindered
0.040 – 0.120	Decidedly perceptible	Hindered
0.120 – 0.400	Unpleasant; tolerable for 1 hr	Much hindered
0.400 – 1.200	Very unpleasant; tolerable for 10 min	Practically impossible
1.200 – 4.000	Extremely unpleasant; tolerable for 1 min	Impossible
4.000	Unbearable	Impossible

The results of these measurements are used here together with results obtained at the University of Tokyo in a recent proposal made by Kanazawa for the vibration limits of ships.[15] The human body may be considered as a mass-spring system with a natural frequency of about 1.5 cps and a percent of damping of 0.12. With this assumption and the sensitivity

TABLE 7

Values for Exponent, n, and Constant, c, for Certain Frequency Ranges

Frequency Range cps	Exponent n	Constant c
0 - 2	3	0.5
2 - 5	2	1
5 - 40	1	5
40	0	200

defined as the energy absorbed in the body, it is possible to explain the human reaction for low frequencies as measured.[15] The classes of reaction can be explained by the Weber-Fechner's law in physiology, namely that the sensation of vibration increases in arithmetical progression while the physical intensity of a stimulus increases in geometrical progression; in other words, double sensation corresponds to four times the intensity of a stimulus.

McFarland[16] and others have noted that the limits of Reiher and Meister have a good experimental basis but question their interpretation that even short exposure to vibrations above the unbearable limit will have a permanent effect on the body. Coermann[17] has exposed subjects to vibrations well above this unbearable range for periods of from 2 to 8 hrs without any apparent permanent injury.

L' Institut de Recherches de la Construction Navale in France conducted a survey on the dis' 'bing effect of hull vibrations on human beings.[18] The su. .y classifies human reactions (Figure 8) in the same manner as in the Reiher-Meister study (Figure 7). However, the ranges are defined by constant accelerations independent of frequencies, i.e., the amplitudes decrease with the square of the frequencies. It is also stated in Reference 18 that vibrations in the horizontal direction shift response level one step to the next higher class, i.e., the body reacts more severely to vibration in the horizontal direction. This is quantitatively in agreement with the results given in Reference 11.

It is naturally of interest to know how the various parts of the human body react to vibrations. Test results seem to indicate that the body reacts as a whole to vibrations below 3 cps,[19] i.e., all measured responses at the body surface have the same phasing. Apparently, however, not very much is known about the actual vibratory response of various organs. The effect of vibrations of shipboard optical equipment on the ability of the eye to detect objects was discussed by Allnutt as early as 1949.[20] Visual task projects, such as reading of instruments under vibrational conditions, are also being conducted by the U.S. Naval Air Development Center.[21] The Wright Air Development Center, Dayton, Ohio, is engaged in a broad program to determine the effect of vibration on humans

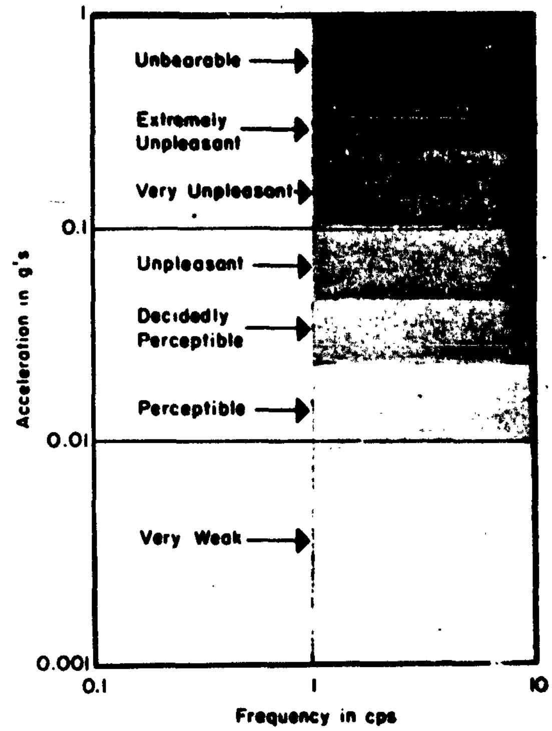

Figure 8 – Human Reaction to Vertical Vibrations in Terms of Acceleration and Frequency

These plots were developed from Reference 18.

It appears that the body has a strong tendency to build up protective measures against vibrational effects. Although vibrations may be uncomfortable or disturbing to humans, Coermann's experiments indicate that this does not necessarily lead to a reduction in operating efficiency. Since vibrations of amplitudes and accelerations above the comfortable limits do appear to give rise to fatigue and exhaustion over extended periods of time, they are undesirable and can be endured only for short periods before efficiency is impaired. The general experience that man can adjust himself to vibration of ships is known and supports this opinion.

An excellent summary of the effects of shock and vibration in man has been made by Goldman and Gierke.[23] It should also be mentioned that the Committee on Hearing and Bio-Acoustics has published a report on the biological effects of vibrations.[24]

EVALUATION OF RESULTS ON HUMAN REACTIONS TO VIBRATIONS FROM EXISTING LITERATURE

Only a few attempts have been made, so far, to define vibration levels on ships which are not objectionable to human beings. It is, however, necessary to set up some

standards based on the vibration level experienced on ships and on the reaction of men to vibrations.

It is not known whether such criteria have ever been formulated. A suggestion for such a formulation is made in Table 6 where the reaction to vibration is related to possible work that can be done by a man under a given environmental condition; unfortunately, the kind of work is not specified.

In this report, the problem is defined in two phases:

(a) Effect of environmental vibration on human beings,

(b) Ability of people to work under environmental vibrations that exist on ships and that cannot readily be altered.

A final permissible environmental vibration level for ships will be controlled by either item (a) and (b), physiological effects, or by mechanical effects, whichever sets the lower permissible limits.

Although many past investigations covered item (a), this problem must be considered as still under study rather than solved. However, as far as vibrations on ships are concerned, it is believed that no systematic investigation has ever been started. The requirements for mechanical effects have been partially solved in the past by an accumulation of practical experience and laboratory tests rather than by a systematic investigation under ship service conditions. Extensive information will be required because increasingly complex and refined apparatus will be installed on ships and will have to be serviced and operated during any weather condition.

Some investigators have tried to correlate the results of various studies to obtain a set of vibration discomfort limits. Such limits are suggested by Goldman.[25] His discomfort level of vibrations in vehicles is fixed at 0.05 g (gravity acceleration) for a frequency range up to 70 cps. Richards[26] believes that this limit should be set at 0.01 g, and Kumai[27] sets the limit for discomfort at 0.015 g. Such an assumption of constant acceleration indicates that the amplitude of vibration for discomfort decreases with the square of the frequency.

The U.S. Navy has assumed some values for vibration levels causing discomfort or acute discomfort in its handbook for ship design;[28] see Figure 9. The figure also includes some straight lines (dashed) indicating vibration amplitudes for given constant levels of acceleration of 0.01 and 0.05 g for comparison as suggested in References 25, 26, and 27. It can be seen that the suggested curves for discomfort and acute discomfort approach a constant acceleration at frequencies of less than about 10 cps but depart somewhat to higher accelerations for frequencies between 10 and 100 cps.

CORRELATION OF SHIP "VIBRATION LEVELS" WITH HUMAN REACTION TO VIBRATION

The acceleration levels in linear vertical acceleration as experienced at the fantail of destroyers and carriers are shown in Figures 5 and 6. The human reaction to vibration is shown in Figure 7.

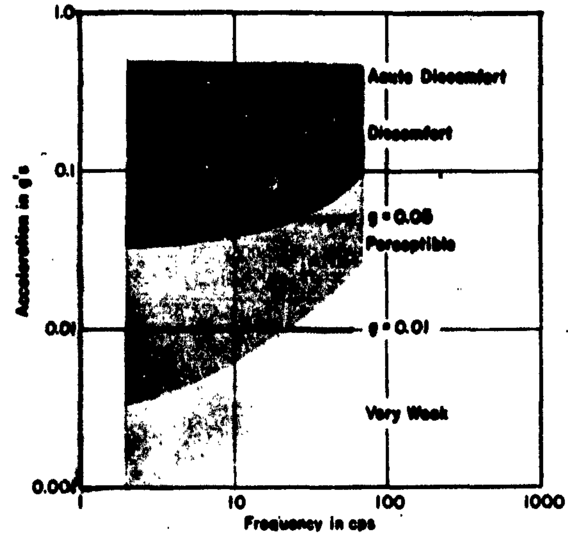

Figure 9 – Suggested Discomfort Levels as Given in References 25, 26, 27, and 28

The frequency range is from about 2 to 60 cps.

Figure 10 shows the classes of human reaction to vibrations (broad bands) combined with the vibration levels at the fantail of a destroyer. A remarkably similar pattern is found between the ship's acceleration for the vibration level and the classes of human reaction for frequencies up to 4 cps. The same holds true for the vibration levels on carriers. The following corresponding classes can be compared:

TABLE 8

Comparison of Classes of Human Reaction and Vibration Levels

Vibration Level	Class of Human Reaction	Percentage of Time for this Class: On DD 692-Class Destroyers*	Percentage of Time for this Class: On ESSEX-Class Carriers*
I	Quite perceptible	11	50
II	Decidedly perceptible	14	25
III	Unpleasant	48	19
IV	Very unpleasant	26	5.5

*From Table 2.

A more severe vibratory condition will be experienced for one percent of the time the destroyer operates at sea in the North Atlantic. It is, however, very probable that larger vibrations occur only in intervals and are, therefore, below the unbearable limit.

Figures 5 and 6 showed very high accelerations for the condition of slamming. This condition is omitted in Figure 8 for two reasons:

(a) Slamming can be considered as an extreme loading of the ship which may even cause structural failure and hence should be prevented by diligent operation, and

(b) the accelerations will only occur intermittently and thus may be endured by the crew.

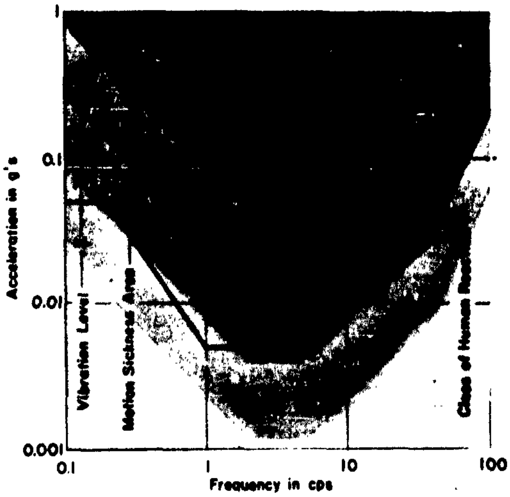

Figure 10 – Comparison of Vibration Levels in DD692-Class Destroyer with Classes of Human Reactions to Vibrations Taken from Figure 7

It should be repeated that the values for acceleration considered here are for the area at the fantail. Accelerations in other areas of the destroyer or carrier can be expected to be considerably smaller even in heavy seas.

The accelerations for frequencies greater than 4 cps corresponding to the various vibration levels cannot easily be compared with the classes of human reaction because they intersect several classes. The accelerations change but little with the sea condition, at the most by a factor of two, and range from decidedly perceptible to extremely unpleasant. It is known that the human reaction to vibration at the fantail can be very unpleasant. This condition can be improved only by reducing the sources of these vibrations.

DISCUSSION AND RECOMMENDATIONS

An attempt has been made to derive linear accelerations for the frequency range from 0.1 to 20 cps; these can be considered realistic accelerations to which crew members on destroyers or carriers may be subjected. The most extreme values experienced in heavy storms lie below the unbearable limit. The vibration level for vibrations on destroyers, shown in Figure 10, consists of several discrete frequencies. These frequencies are associated with natural modes of hull vibrations excited by wave action and the propeller-shaft system. Extreme values occur only occasionally and can, therefore, be tolerated. As an example, PT boat crews have tolerated accelerations of about 6 g in very rough water.[29] Other studies also indicate that the human body can sustain very high accelerations for short periods of time.[22] Thus, test results seem to indicate a considerable adjustment of the human body to vibrations. Such an adjustment is certainly to be expected on ships where the crew is exposed to vibration for a long period of time.

It is indeed fortunate that the vibration level on ships is relatively low in the range (2 to 5 cps) where humans are most susceptible to accelerations. Transition of the reaction of the human body to vibration occurs in this range. Below 3 cps, all parts on the surface of the body react in phase[19] while above this frequency, parts of the body vibrate out of phase (i.e., head to shoulder out of phase). At higher frequencies, the body can tolerate higher accelerations because of a proportionally large increase in damping effects in the body.

Under the existing vibratory conditions a crew member is required to fulfill certain duties necessary to keep the ship in operating condition. Not much is known about the crew's capabilities to perform a work under severe environmental vibrations. Tests, however, should be devised so that the effect of severe environmental vibration on work can be measured. The effects of vibrations on work as defined in Table 6 are unrealistic, at least as far as crew duties are concerned. It is known that work has been done on ships at higher accelerations than those corresponding to Table 6 where, for $K = 0.4$, work was considered practically impossible. Measurements of vibrations have been made successfully on ships in heavy storms with delicate instruments by trial groups of the Model Basin.

A further comparison of the actual vibratory level on ships may be made with the present acceptance tests for vibrations of equipment which are prescribed in military standards.[30] These tests cover a range from 5 to 33 cps. The lines in Figure 11 indicate the accelerations at which

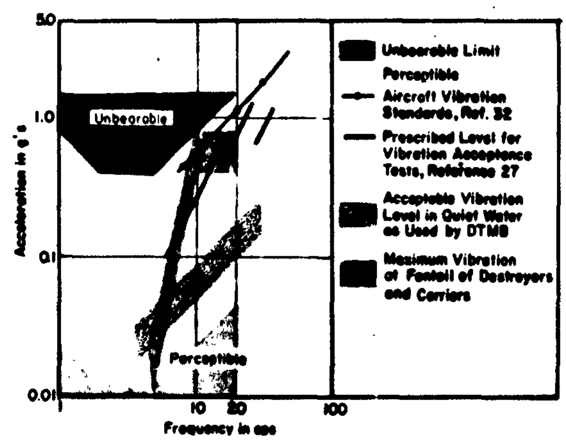

Figure 11 – Maximum Vibration Levels at Fantail of DD692-Class Destroyers and Acceptable Vibration Levels as Indicated

equipment should not fail. These values are in the range of accelerations corresponding to maximum values on surface ships. They appear to be realistic for endurance tests. It remains, however, to be determined whether or not the crew can still operate the equipment.

The acceleration values usually assumed by the Model Basin as acceptable vibrations for destroyers[31] are also shown in Figure 11. The acceleration values of these norms are less than those experienced in heavy seas. In the range between 4 and 30 cps, the norms are realistic. Maximum vibratory accelerations acceptable for aircraft, as used by the British,[32] are also shown in Figure 11. They lie slightly above values accepted by the U.S. Navy.

It would be helpful to compare the operational efficiency of a crew with various physiological changes at severe vibration levels, but the author knows of no published studies in this area. Inasmuch as a designer should have such information available, it is recommended that criteria be established as a joint effort by a team of medical and engineering experts. As an example, it may be required that certain well-defined orders should be executed by as many of the crew as possible under the supervision of trained observers or an automatic recording device to measure human reactions should be developed to further our knowledge.

Acceleration limits with constant acceleration over the frequency range of interest seem to be unrealistic and possibly misleading. The development of delicate complex equipment makes further research in the field of human reaction to ship vibrations mandatory in order to help ship designers to assure the efficiency and safety of a ship and its crew.

SUMMARY

1. A search of literature on human reactions to vibrations indicates that the work in this field is helpful in establishing classes of reactions.

2. Vibration levels, relating ship length with a sea state of defined wave length and height, are established and outlined in detail for the case of a destroyer and a carrier.

3. The correspondence between classes of human reactions and the suggested vibration levels in ships is used for establishing norms of vibration for human reactions on naval ships.

4. It is advisable to classify the type of work that has to be done to keep a ship in operating condition at each vibration level.

5. When equipment is to be operated by the crew in heavy confused seas, design criteria should be established from tests devised as a team effort by human engineering specialists.

6. The designer of equipment should know not only the mechanical load on the equipment due to vibrations in heavy seas but also the service he may expect from a crew member under such conditions.

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